NBS TECHNICAL NOTE 954

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

SPECTRAL RADIOMETRY:

A New Approach Based on Electro-Optics

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SPECTRAL RADIOMETRY:
A New Approach Based on Electro-Optics

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SPECTRAL RADIOMETRY: A NEW APPROACH BASED ON ELECTRO-OPTICS*

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Progress in developing a new approach to radiometry based on electro-optical technology is discussed. A feasibility experiment that demonstrates and motivates the new approach is described. The laser-based, characterization facility that plays a central role in the new approach, including the electrically calibrated pyroelectric radiometer that provides the absolute radiant power measurements, and recent investigations of silicon photovoltaic detectors that were performed on the facility are all described. Alternatives for extending the wavelength range of the new approach are also discussed.

Key Words: Absolute radiometry; detector; electrically calibrated detectors; laser power measurements; pyroelectric detectors; radiometry; silicon cell; silicon detector; silicon photodetector.

1. INTRODUCTION

The blackbody emerged as a standard source of the quantity and spectral distribution of radiation following intense experimental and theoretical study during the late 19th and early 20th century [1][1]. The experimental studies of the total quantity of blackbody radiation were carried out with electrically calibrated detectors [2]. Yet with the exception of these experimental studies [3], the starting point in measurement practice has been the blackbody rather than the electrically calibrated detector [4].

Since 1960, however, this situation has begun to change. A number of new electrically calibrated detectors have been built for laser radiation [5], solar radiation [6], and traditional radiometric and photometric applications in the national laboratories [7]. Recent remeasurements of the Stefan-Boltzmann constant have demonstrated that the long standing inconsistencies [8] between blackbody and electrical calibration radiometry have been resolved [9]. One laboratory has even based its spectral radiometry on an electrically calibrated detector; still using a blackbody, but determining its distribution temperature with the detector and colored glass filters [10].

In this paper, we will discuss a new approach to spectral radiometry. It is based on electrically calibrated pyroelectric detectors [11] and other recent electro-optical devices, but does not employ a blackbody. First, we will describe a previously reported [12] experiment that demonstrates the feasibility of the new approach and motivates our current efforts. Next we will describe the laser-based, characterization facility that replaces the blackbody in the new approach, including a description of the electrically calibrated pyroelectric detectors that provide absolute radiant power measurements for the facility. Then we will turn our attention to recent studies [13] of silicon photovoltaic detectors that have been carried out using the facility. These studies are also of interest outside the context of the new approach to radiometry. We conclude by discussing alternatives for extending the wavelength range of the new approach, including a discussion of the recent application of an electrically calibrated pyroelectric detector to pulsed laser measurements [14].

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*This is an extended version of a paper presented at the 7th International Symposium of the IMEKO Technical Committee on Photon-Detectors, Braunschweig, West Germany, May 17-19, 1976.

[1]Figures in brackets indicate the literature references at the end of this paper.

2. FEASIBILITY EXPERIMENT

The arrangement of the experiment to demonstrate the feasibility of a new approach to radiometry is shown in Fig. 1. The ratio of the monitor cell reading to the power in the laser beam, as measured with the electrically calibrated pyroelectric detector, was recorded at 10 nm intervals from 570 nm to 630 nm (the tuning range of rhodamine 6G). The time constant of the pyroelectric and monitor electronics were not matched, and the laser beam power fluctuated significantly. Therefore, these measurements suffered significant random noise, the standard deviation of a single measurement being $\sim\pm 0.5$ percent. However, the time constants of the electronics of both detectors were on the order of a few seconds, so it was possible to repeat a wavelength scan in a few minutes, permitting a large quantity of data to be accumulated for averaging. The 126 data points obtained in this way were fit to a linear equation, giving the monitor cell reading per unit power in the test beam as a function of wavelength with an estimated [15] three standard deviation interval of ±0.25% around 600 nm and to somewhat greater uncertainty on the wings of the wavelength interval.

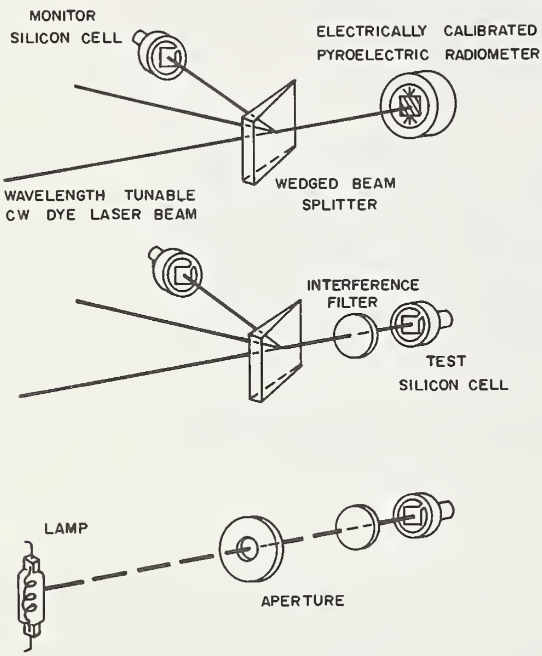

Fig. 1: Experiment arrangement for measuring the power per unit area per unit wavelength from a lamp using a filtered silicon cell whose absolute spectral response has been measured with respect to an electrically pyroelectric radiometer using wavelength tunable cw dye laser radiation.

The electrically calibrated pyroelectric detector was replaced in the laser beam by a silicon cell fitted with a three cavity interference filter of nominal 10 nm bandpass at 600 nm. The ratio of the filtered cell reading to the monitor cell reading was recorded over the 570 nm to 630 nm range. The sampling interval was varied over the wavelength range so that the spectral response was densely sampled in the center and on the top edges of the bandpass, but less densely in the wings. The bandwidth of the laser radiation was less than 0.1 nm, but no channel spectral interference effects [16], such as would be expected with a plane parallel piece of glass [17], were observed. Since the monitor and test cell electronics had matched time constants, the effect of laser power fluctuations were largely eliminated yielding a standard deviation of a single measurement of 0.2%.

A total of about 80 ratios of the test cell to monitor cell readings were recorded as described above. These ratios were multiplied, wavelength by wavelength, by the linear curve derived to represent the ratio of the monitor cell reading to the power in the test beam (described above) to yield the spectral response of the filtered silicon cell. These data are shown in Fig. 2. Notice that the abscissa was inadvertantly mislabeled in ref. 12 (Fig. 1), and has been corrected here.

The linearity of the filtered silicon cell was verified by comparison with the electrically calibrated pyroelectric over the range of photocurrents encountered in the above experiment and to be expected in the lamp measurements described next. Sensitivity to polarization and location on the filtered cell were also investigated, and uncertainties for these effects were calculated.

The filtered silicon cell was now fitted with an aperture of known area and used to measure the radiant power per unit wavelength per unit area (spectral irradiance) emitted by two different quartz halogen lamps at a wavelength of 602 nm and a distance of 50 cm from each lamp. The detailed mathematical procedure is described in ref. 12. A spectrophotometer was used to verify that the filter transmission was less than 0.01% outside of the 570 to

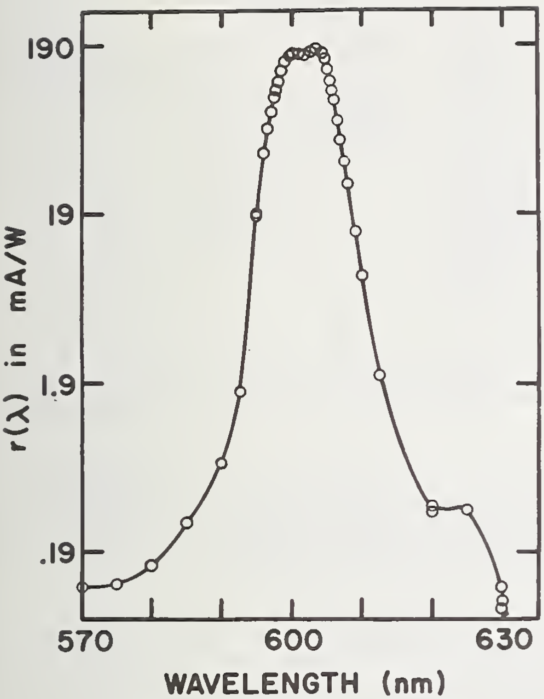

Fig. 2: Measured spectral response of the filtered silicon cell as a function of wavelength (from ref. 12). Note that the ordinate of this figure was inadvertantly mislabeled in ref. 12 and has been corrected here.

630 nm wavelength region. Nominal spectral irradiance curves [18] were used to represent the lamp output outside of this wavelength region. In this way it was possible to obtain a correction factor and an upper limit of error for the response of the filtered silicon cell to lamp radiation falling outside of the dye laser measurement range.

The results of this procedure are shown in Fig. 3. Also shown there are values obtained by calibration of the lamp with respect to blackbody radiation characteristic of the temperature of freezing gold.[19] Thus Fig. 3 shows a comparison of the new approach to spectral radiometry with the traditional approach based on a blackbody. The difference of 1.0% ±0.3% shown there is well within the combined estimated uncertainties of the two approaches. These are ±1.0% for the calibration of the filtered silicon cell with respect to the electrically calibrated pyroelectric detector, ±1.0% for the calibration of the lamp and ±0.4% for the alignment, drift etc. of the lamp. A more detailed error analysis is presented in Fig. 4. It is of some interest that the uncertainties associated with the aperture area and the variations in response over the pyroelectric receiver have already been reduced significantly below the values listed in the figure.

Having demonstrated the comparability of the two approaches to spectral radiometry at the one percent level, we anticipate the replacement of the interference filter with an electronically tunable filter such as the acoustically tuned optical filters (ATOF) that have been the subject of much interest recently [20].

3. LASER-BASED CHARACTERIZATION FACILITY

This facility plays a major role in our study of the new approach to radiometry. For most radiometric purposes, cw lasers approximate delta functions in wavelength, position, direction, and polarization. This greatly simplifies precise characterization of optical instruments with respect to variations of these parameters. Computer control assists these characterizations as well as those with respect to time, temperature, power level and power density. The power in the laser beam is measured with respect to electrical standards using an electrically calibrated pyroelectric radiometer. The combination of laser facility and the radiometer is synergistic, since the facility is used to determine the equivalence of the radiometer's response to radiant and electrical power.

Our facility is modular, providing flexibility for growth, as well as for a variety of characterization activities. This flexibility has also proven useful in support of other activities that require accurately known quantities of monochromatic power. These include studies of photoelasticity [21], chemical actinometry [22], and photorheology of blood [23]. Figure 5 is a schematic diagram of the present facility. It is set up on a 4' x 18' rigid-honeycomb, optical table made from three 4' x 6' sections. The top of the table is 1/4" thick magnetic steel with tapped 1/4-20 mounting holes on 1" centers.

The numbered circles in Fig. 5 represent kinematically mounted mirrors that permit removal and simple realignment. The alignment apertures have proven useful for preliminary

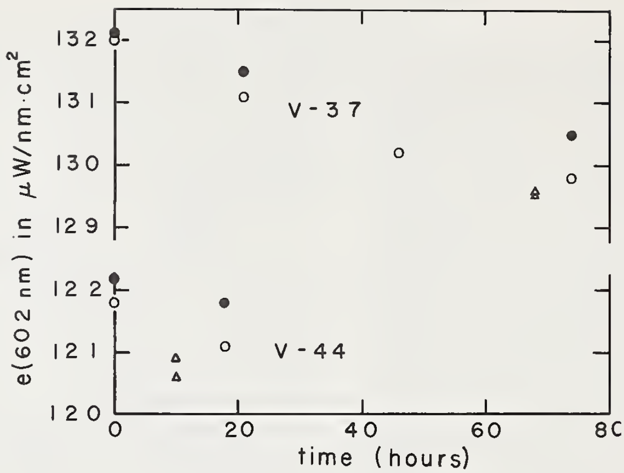

Fig. 3: Comparison of the values of the spectral radiant power density (spectral irradiance) at 50 cm from two quartz-halogen projection lamps as measured by a filtered silicon cell whose absolute response was measured with reference to an electrically calibrated pyroelectric detector using a dye laser (Δ), and measured with reference to the radiation from a blackbody at the freezing point of gold (•) as a function of the burning time on the lamps. The work necessary to obtain these latter values was not complete in time for the publication of ref. 12, which included only the preliminary values (o) available to us at that time.

	SILICON PHOTODIODE/ INTERFERENCE FILTER, BASED ON PYROELECTRIC		NBS LAMP STANDARD OF SPECTRAL IRRADIANCE BASED ON A BLACK-BODY AND TEMPERATURE	
Primary Reference	Area uniformity	0.5	Au melting point	0.5
	Power equivalence	0.2	Measurement of IPTS temperature and quality of the blackbodies	0.5
	Power measurement	0.5		
	Duty cycle	0.04		
Transfer to Secondary Standard	Area uniformity	0.4	Spectral radiance and irradiance transfers	0.7
	Spectral integration	0.6		
	Polarization	0		
Measurement Against Secondary Standard	Linearity	0.1	Alignment	0.4
	Aperture area	0.6	λ interpolation	0.2
			Drift	0.5

Fig. 4: Comparison of uncertainties in the measurement of the spectral power density (spectral irradiance) from a lamp at a wavelength of 602 nm using two different approaches.

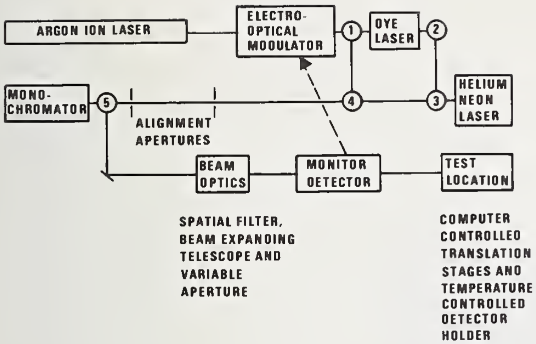

Fig. 5: Block diagram of the laser-based radiometric characterization facility.

alignment of the test beam from the different radiation sources. By suitable placement of the appropriate mirrors it is possible to direct the argon-ion laser radiation into either the test beam, the spectrometer for wavelength calibration, or the dye laser where it pumps a jet of fluorescent dye which in turn lases. The dye laser beam can be directed into the test beam or into the spectrometer for calibration of the dye laser wavelength scale. Similarly, it is possible to direct the HeNe laser beam into the test beam or into the spectrometer.

The power in the test beam is stabilized using an electro-optic modulator (EOM) in a feedback loop [24]. Part of the radiation in the test beam is split off via a reflection from a wedged quartz beamsplitter. This radiation is directed onto a diffuser covering the active area of a uv-stable silicon photodiode. The 1 cm^2 diode used in our system is a UV444B manufactured by EG&G.[25] Both the beamsplitter and the diode are mounted in a temperature controlled housing shown in Fig. 6. The temperature of the housing is maintained at a few degrees above ambient to within ±0.1 C using the simple thermistor controlled DC power amplifier shown schematically in Fig. 7.

The output from the silicon photodiode is amplified in a high gain DC servo amplifier illustrated in Fig. 8. An AD52K manufactured by Analog Devices is used as the current to voltage converter on the input stage of the amplifier. The output of this amplifier is fed onto an adjustable laglead compensation network and also to a buffer amplifier which can be used to monitor the silicon detector. The output of the compensation amplifier feeds one junction of a X100 summing amplifier. The other junctions allow for the injection of both an offset bias which is used to control the DC power level of the test beam and an external auxiliary signal. The auxiliary input is needed for such functions as stable sinusoidal modulation, etc. The X100 amplifier feeds another X1000 amplifier for additional DC gain. This signal is then used to drive a X10 high voltage amplifier which in turn provides the necessary 240 volt P-P half wave voltage for the EOM. This high slew rate, high voltage, low drift amplifier is an AM302B manufactured by Datel Systems.

The modulator itself is a 45° X cut ADP crystal mounted in an index matching fluid enclosed in an aluminum housing for thermal stability. The Model 28 modulator, supplied by Coherent Associates, is capable of handling optical powers up to 6 watts in the 300 to 800 nm spectral range. In practice we have used the device to stabilize lines from 257 nm to 1.09 μm.

Depending upon the source and wavelength of the laser radiation, beam power stabilities of 0.1% to 0.01% have been obtained within a dc to 5 kHz bandwidth with the system described above. By using faster amplifiers it is possible to extend the bandwidth to several MHz with only a small degradation of performance.

The spatial filter, beam expanding telescope and variable aperture in Fig. 5 are used to "clean up" the laser beam, and to select the uniform central region of gaussian and/or diffraction limited beam patterns (with consequent reduction of beam power) for applications requiring a relatively uniform beam. The computer controlled translation stages are used to investigate the angular and spatial sensitivity of detectors, optical elements and instruments of moderate size. A temperature-controlled detector holder attached to the translation stages allows the investigation of the sensitivity of various parameters to small temperature variations above ambient. The present wavelength coverage of the facility is shown in Fig. 9. Also shown there is the wavelength range to which we hope to expand the facility in the near future.

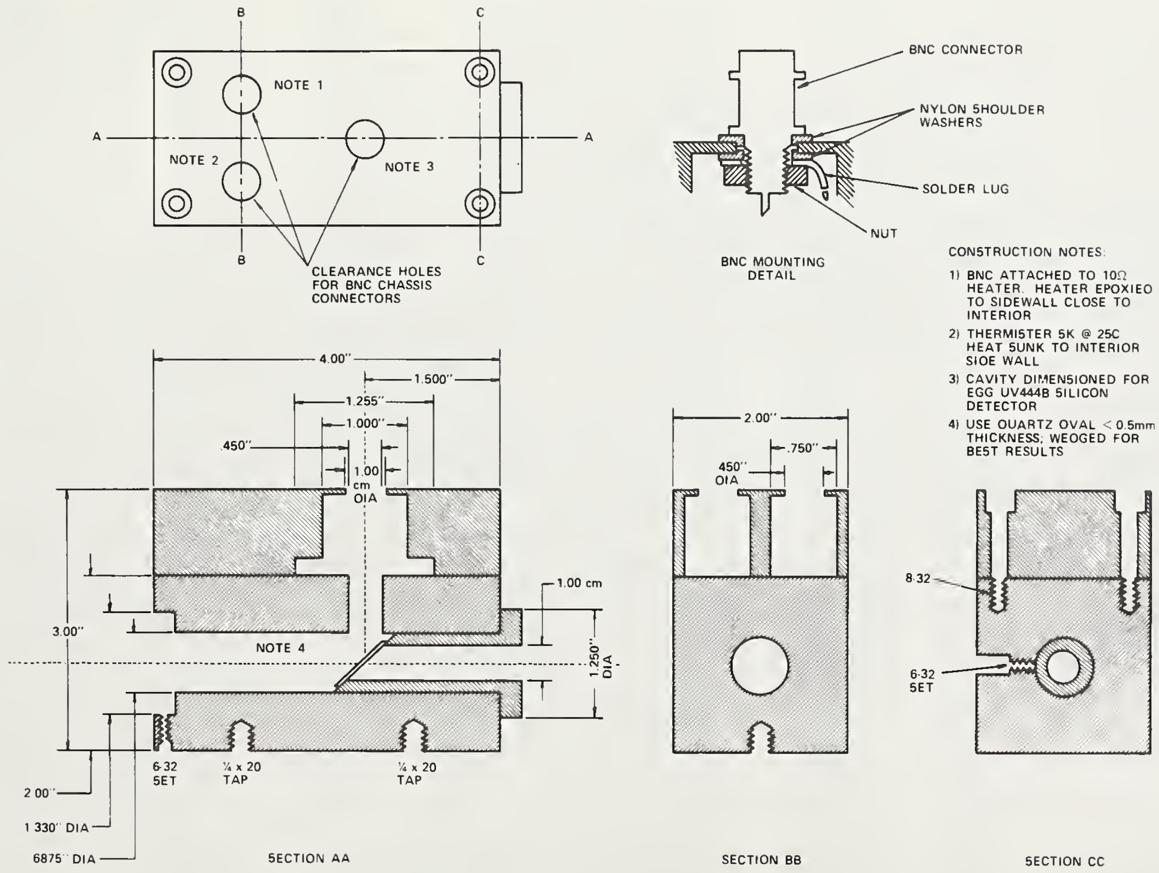

Fig. 6: Beam splitter and temperature controlled detector housing.

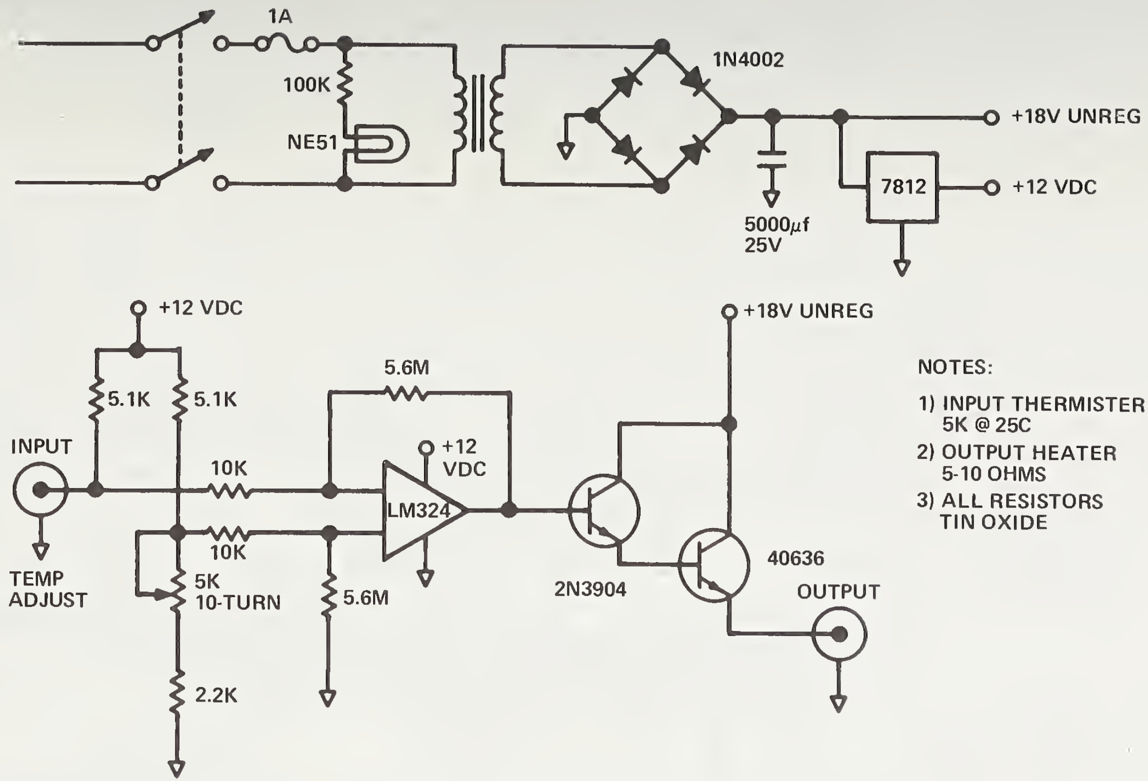

Fig. 7: Temperature controller.

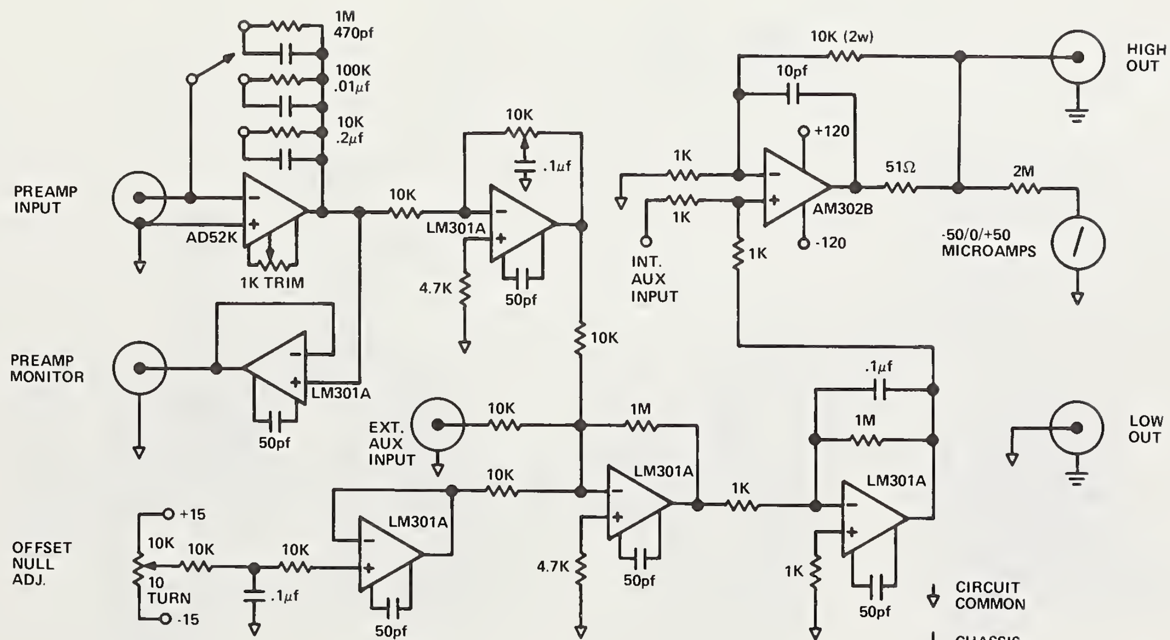

Fig. 8: Laser beam power stabilization servo amplifier.

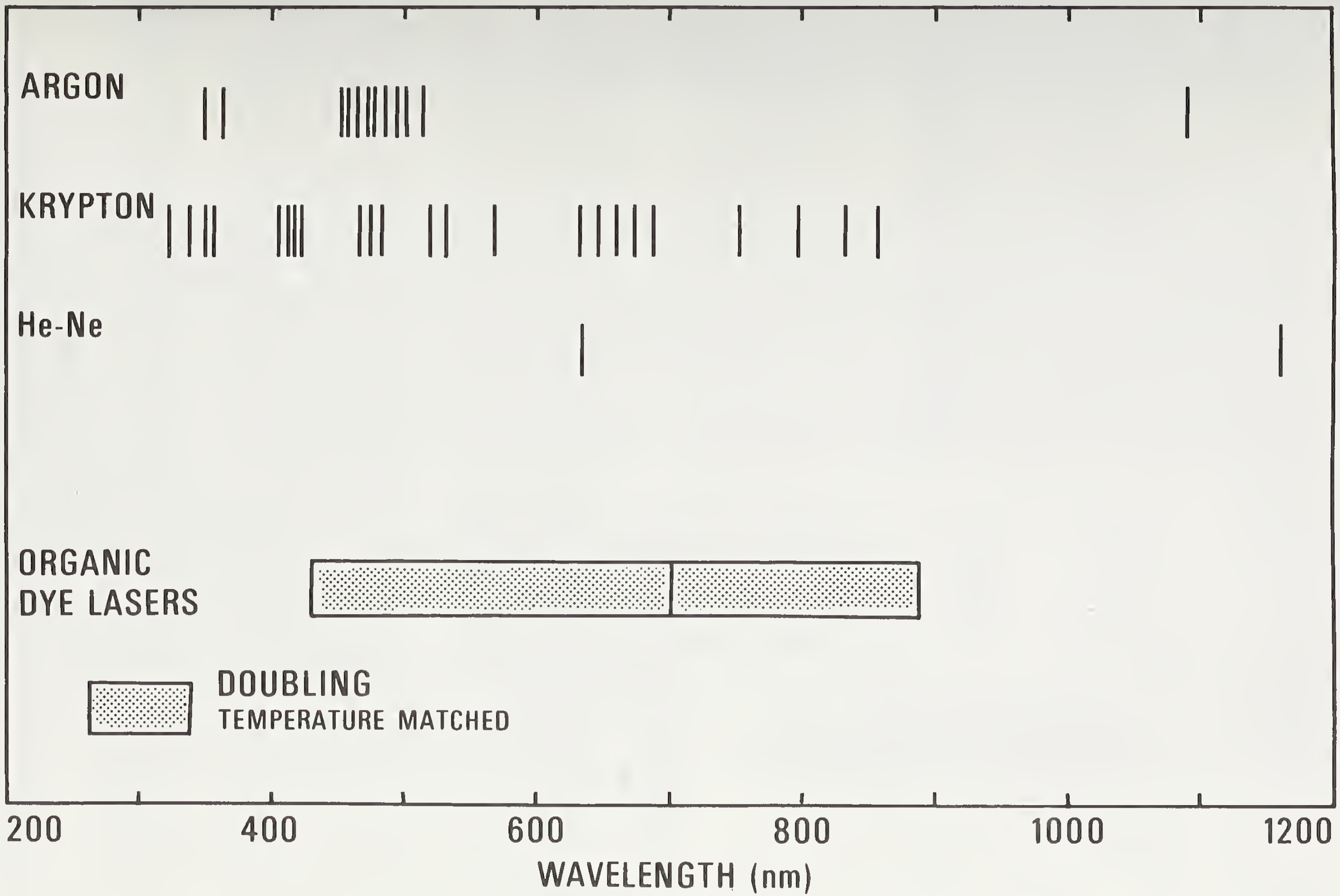

Fig. 9: The present wavelength range of the NBS laser based, characterization facility and the wavelength range to which we hope to extend it in the near future.

4. ELECTRICALLY CALIBRATED PYROELECTRIC RADIOMETER

Figure 10 presents a cross-sectional view of an electrically calibrated pyroelectric detector with isolated heater and transducer circuits.[26] The isolation is obtained by grounding the vacuum deposited gold on the back surface of the plastic film. Figures 11 and 12 show the electrical circuitry for waveform independent [27], null radiometer based on this type of detector. Such a system responds to the difference in the areas under the pulses of radiant and electrical power, rather than to the first harmonic of the waveform. Thus modulators such as choppers, whose output waveform depends upon the distribution of the incident radiation in the entrance aperture of the modulator can be used. However, it is necessary that the energy content of the modulator's output pulses be independent of the distribution of the incident radiation. Furthermore, the transducer and signal processing electronics must preserve the area under the pulses within the gating time of the synchronous demodulator. Thus wideband electronics must be used.

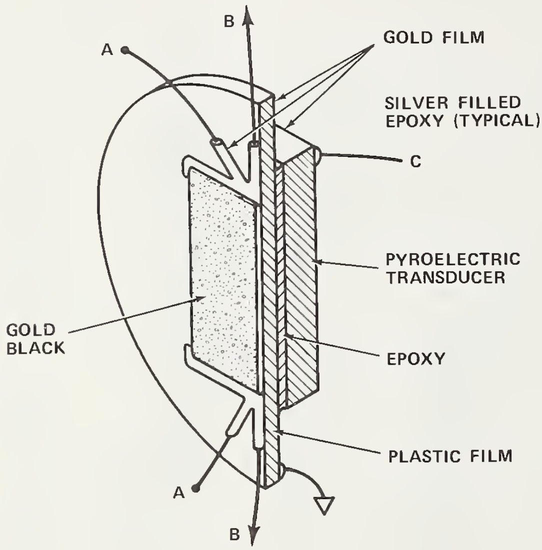

Fig. 10: A cut-away view of an electrically calibrated pyroelectric detector with isolated heater and transducer circuits.

The operation of the radiometer is as follows. The gain of the variable amplifier in Fig. 11 is varied until the output of the low pass filter is null. The gain can be controlled manually or by feedback from the low pass filter. Once the null is achieved, the unmodulated radiant power is given by

$$P_R = P_E \, (D_E/D_R) \, F, \qquad (1)$$

where P_E is the electrical power computed by the circuitry of Fig. 12, D_E and D_R are the duty cycles of the electrical and radiant modulation waveforms, and F is a correction factor that accounts for incomplete equivalence between the detector's response to electrical and radiant heating. The measurements of D_E and D_R are routine, but the measurements that determine F are less straightforward. They are similar in principal to the measurements described in ref. 7 (J. Geist, 1971) and they have been discussed briefly in other papers cited in ref. 7. Such a system appears capable of better than one percent accuracy from around 200 nm to beyond 20 μm.

It is also possible to build a null radiometer based on electrically calibrated pyroelectric detector in which the heater and transducer circuits are coupled.[28] The absence of the ground plane, insulating plastic film and epoxy joint simplifies the construction of the detector, but requires somewhat more sophisticated signal generation and processing electronics. A commercial system employing this type of detector is currently available.[29] The principal reason for the choice of the latter design for commercialization was a supposed problem in obtaining uniform response over the detector surface due to the epoxy joint. However, the problem turned out to be caused in fact by imperfections in the transducer crystals, so either configuration can be used.

Similarly it is possible to base the circuitry on narrow band (tuned) electronics.[30] In this case the radiometer responds to the first harmonic of the waveform, so the angular aperture of the chopper must be suitably limited. It will be some time, if ever, before the optimum system design is unequivocally established.

5. SILICON PHOTODETECTOR STUDIES

The increasingly stringent requirements on silicon photovoltaic detectors in modern radiometric measurements require a thorough understanding of the basic characteristics of

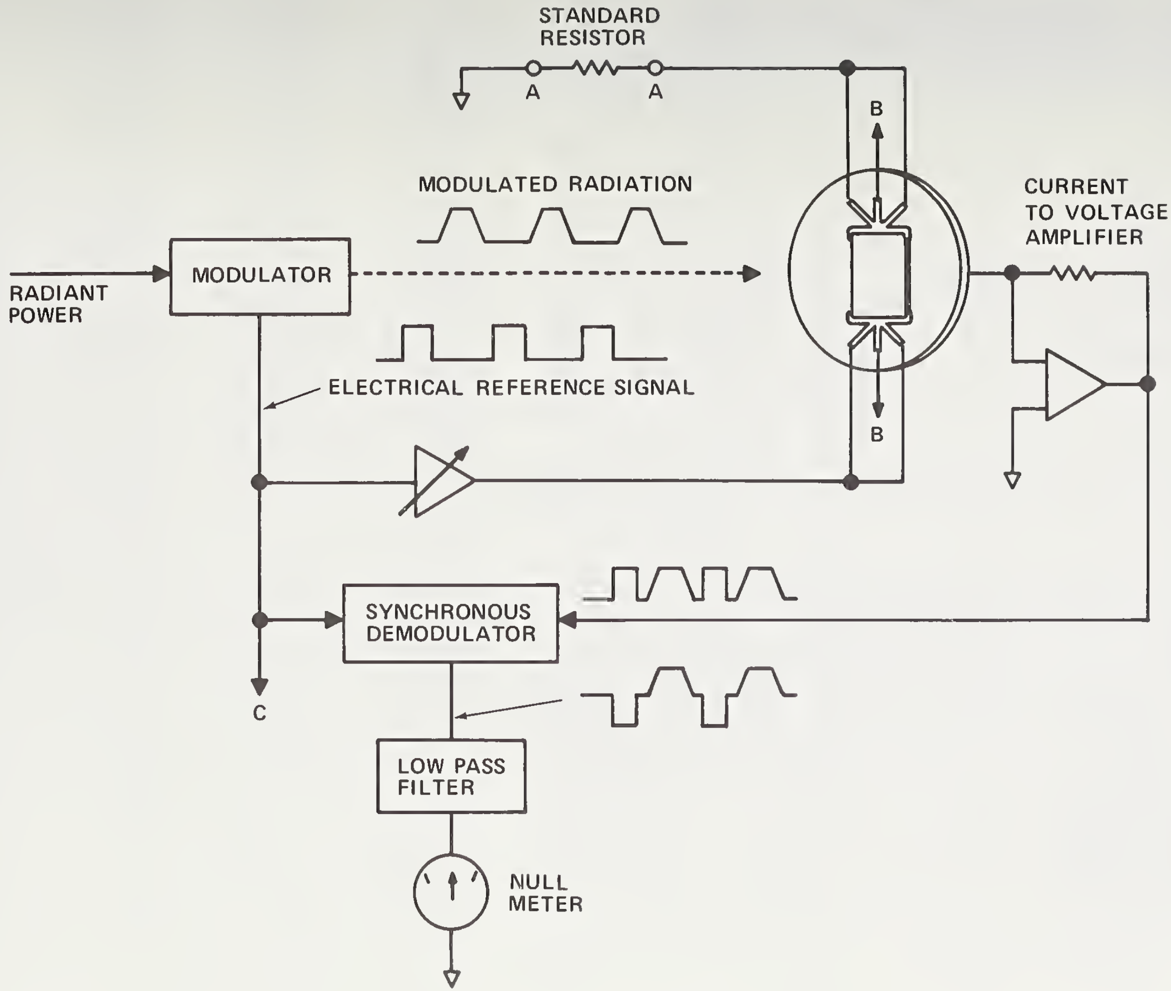

Fig. 11: Signal generation and detection electronics.

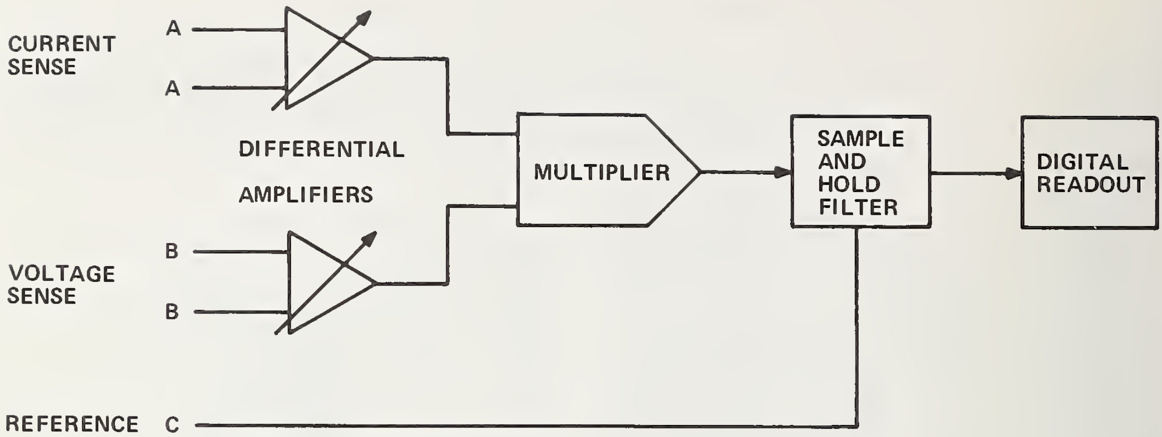

Fig. 12: Electrical power computation electronics.

these devices. Several instances of anomalous behavior with resulting degradation of performance illustrate the importance of careful characterization of these detectors.

One such recently observed problem [31] is the enhancement of spectral response of certain types of silicon pn photodiodes by exposure to near ultraviolet radiation. In this study, a 2 mm diameter area of the detector surface was irradiated by a reasonably uniform laser beam at 364 nm with an average incident power density of 4 mW/cm^2. The responsibity of this area increased about 25% during the course of one hour. When beams of other wavelengths were scanned across the detector surface, the enhancement of the response at the "burned in" spot was very evident, even at 633 nm. Figure 13 is a plot of the relative responsibity of a "burned in" detector as a function of position on the detector surface for various incident wavelengths of radiation. This enhanced responsibity decreased back to normal over a period of several days.

It was also observed that the uniformity of response as a function of position across some silicon photodiodes begins to degrade in the blue region of the spectrum. One type of detector, uniform within .5% over the 500 to 700 nm wavelength region, exhibits non-uniformities larger than several percent at wavelengths below 460 nm. An improved type of detector was found to be more uniform in the blue region, but also degrades at shorter wavelengths. Furthermore, this type of detector shows no UV enhancement effect.

Additional studies of silicon detectors, done by irradiating a 2 mm area with 6 mW/cm^2 radiation at 313 nm from a mercury arc, produced similar results. The responsibility enhancement was exponential with time, reaching a saturation level of about 25% relative increase in three hours. No enhancement effect was seen when using 405 nm radiation.

Several possible explanations of the enhancement effect have been investigated experimentally. The results, presented in detail elsewhere [32], will be discussed briefly here. A possible explanation of the effect lies in the presence of extra available energy states due to crystalline discontinuities and impurities trapped near the surface of the detector. One simple model that was considered postulates an impurity material near the detector surface which possesses an intermediate metastable state that can only be populated by incident ultraviolet photons. Electrons in this intermediate state could then be further excited into the conduction band by absorption of other ultraviolet or visible photons. These additional carriers would result in an enhanced responsivity until the intermediate levels were depleted.

In a mechanism of this type, one should be able to depopulate the metastable state by irradiating the enhanced area with visible light. Experiments were performed in which the relative response of an enhanced detector was recorded as a function of time. This was done first with the detector in the dark, except for brief responsibity measurements, and then with the detector irradiated with visible light. These measurements were performed at a

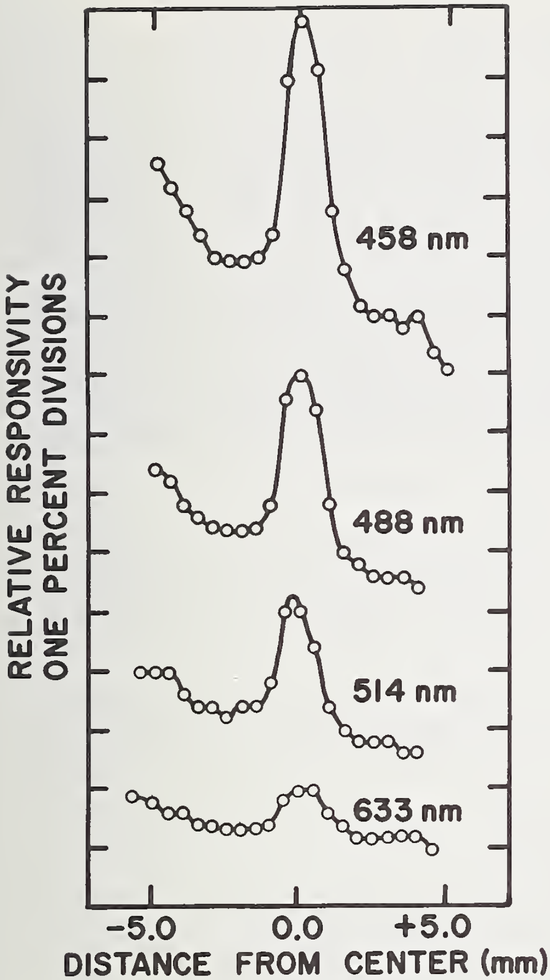

Fig. 13: Relative response of a silicon cell as a function of wavelength and position through a 2 mm diameter region of the cell that was irradiated by 364 nm wavelength, 4 mW/cm^2 nominal power density radiation for one hour.

variety of wavelengths from 405 nm to 633 nm. In no case was the enhancement seen to decrease with a time constant different from the approximate three hour time constant observed in the dark. This results rules out this simple model.

Another possibility considered was that, due to some physical phenomenon in the detector surface, the reflectance of the ultraviolet irradiated area would decrease, resulting in an increased number of photons absorbed and an apparent increased responsivity. To check this hypothesis, one of the new type of ultraviolet stable detectors was employed. This stable detector was irradiated with ultraviolet radiation to ascertain that it did indeed show no enhancement effect. The stable detector was then used to measure the reflectance of the test detector as a function of time while it was being irradiated with 3 mW/cm^2 of 334 nm radiation, and again using 0.4 mW/cm^2 of 254 nm radiation. Although a response enhancement of 25% was observed, no change in the reflectance of the detector surface was observed.

Other possible models have been proposed to explain this effect. In one such mechanism, surface or impurity states between the conduction and valence bands are affecting the apparent quantum efficiency by trapping photon generated carriers. Electrons trapped in these extra states, together with the positive ions left behind, alter the potential barrier in the surface region, as well as other parameters such as conductivity and recombination rate. The spectral response of the detector is thus directly related to surface state availability and population. More detailed experimentation would be required to isolate the specific mechanism involved in the enhancement effect. Perhaps the ultraviolet photons ionize a sufficient number of impurity atoms to result in a significant depopulation of the surface states, causing an increased detector efficiency due to the reduced surface energy barrier. The response could then be observed to slowly decrease again in the dark, as the impurity induced states once again trap electrons and the detector returns to its former condition.

6. CONCLUSION

We have reviewed current progress in developing a new approach to radiometry. In this approach wavelength tunable, cw lasers replace traditional blackbody sources, and electrically calibrated pyroelectric detectors provide the absolute power scale. Since laser radiation is highly concentrated with respect to wavelength, position, direction, and polarization, the new approach facilitates the detailed characterization of radiometric instrumentation. Finally, we observe that the principal impediment to the full utilization of the new approach at any arbitrary wavelength is the lack of wavelength tunable, cw lasers in certain regions.

There are two promising alternatives for expanding the wavelength range. The first is to wait for the development of new wavelength tunable, cw lasers in those regions where they presently do not exist. Wavelength tunable, pulsed lasers, in conjunction with frequency doublers, mixers and parametric amplifiers, already provide continuous coverage from 220 nm to 30 µm, and the cw capability has rapidly followed the pulsed capability in the past.

The second alternative is to extend the techniques discussed above to pulsed lasers. As a first step in this direction, we have recently shown that pyroelectric radiometers are compatible with high accuracy measurements of pulsed laser radiation.[33] We demonstrated that the piezoelectric response (of the pyroelectric detector) to the acoustic pulses generated during the absorption of impulsive energy was on the order of one percent of the pyroelectric response to the thermalized absorbed energy, and is capable of correction. An oscilloscope trace illustrating this result is shown in Fig. 14. The temporal resolution of the thermally and acoustically derived pulses that is shown in the figure is due to the presence of a thin plastic film between the absorbing layer and the pyroelectric transducer, as was shown in Fig. 10. Acoustic waves propagate across this film in something of the order of twenty picoseconds, while the thermal pulses require milliseconds to diffuse across it. To complete the extension, silicon photodiodes or other stable solid state detectors with linear response at the high photon current densities existing in pulsed laser radiation must be obtained and accurately characterized.

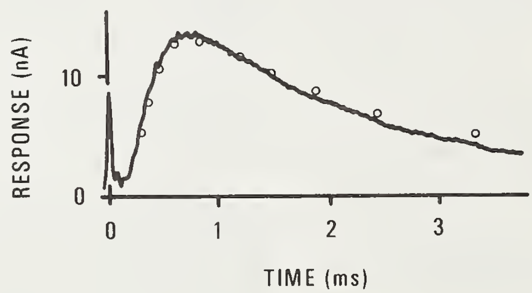

Fig. 14: An oscilloscope trace showing the relative piezoelectric (area of first pulse) and pyroelectric (area of second pulse) responses to the absorption of impulsive radiant power. The circles show the result of a calculation of the expected pyroelectric response for a diffusive heat flow.

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16. ABSTRACT (*A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.*)

Progress in developing a new approach to radiometry based on electro-optical technology is discussed. A feasibility experiment that demonstrates and motivates the new approach is described. The laser-based, characterization facility that plays a central role in the new approach, including the electrically calibrated pyroelectric radiometer that provides the absolute radiant power measurements, and recent investigations of silicon photovoltaic detectors that were performed on the facility are all described. Alternatives for extending the wavelength range of the new approach are also discussed.

17. KEY WORDS (*six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons*) Absolute radiometry; detector; electrically calibrated detectors; laser power measurements; pyroelectric detectors; radiometry; silicon cell; silicon detector; silicon photodetector.

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